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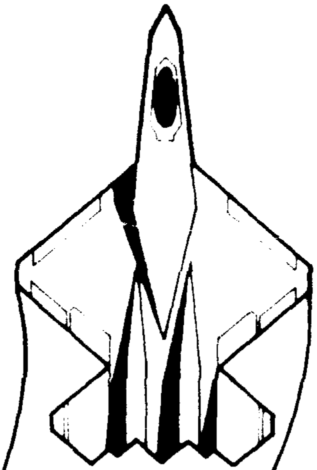

CENTER for AEROSPACE DOCTRINE, RESEARCH and EDUCATION

Cost-Performance Choices in Post-Cold War Weapon Systems

RAYMOND E. FRANCK, JR, Col, USAF

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Cost-Performance Choices in Post-Cold War Weapon Systems

by

RAYMOND E. FRANCK, JR., Col, USAF

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Contents

Foreword

The stunning changes in the complexion of international politics that began late in the decade of the 1980s and continue today will profoundly affect the American military establishment as a whole, and the US Air Force in particular. Decisions about the future course of the military will be made in the early part of the 1990s which will essentially determine the course of the US Air Force well into the next century. Decisions of such importance require thoughtful consideration of all points of view.

This report is one in a special series of CADRE Papers which address many of the issues that decision makers must consider when undertaking such momentous decisions. The list of subjects addressed in this special series is by no means exhaustive, and the treatment of each subject is certainly not definitive. However, the Papers do treat topics of considerable importance to the future of the US Air Force, treat them with care and originality, and provide valuable insights.

We believe this special series of CADRE Papers can be of considerable value to policymakers at all levels as they plan for the US Air Force and its role in the so-called postcontainment environment.

DENNIS M. DREW, Col, USAF
Director
Airpower Research Institute

About the Author

Col Raymond E. Franck, Jr.

Col Raymond E. Franck, Jr., is permanent professor and head, Department of Economics and Geography, United States Air Force Academy (USAFA). He was born in Sac City, Iowa, 28 August 1945. He graduated from Denison Community High School, Denison, Iowa, in 1963 and entered the USAFA that year, graduating in 1967. The recipient of a National Science Fellowship, he then entered Harvard University where he received his Master's and Doctorate in Economics. Colonel Franck is also a graduate of Squadron Officer School, Air Command and Staff College, the National Security Management course, and Air War College.

Colonel Franck entered Undergraduate Pilot Training at Columbus Air Force Base (AFB), Mississippi, in 1969 and earned his pilot wings in 1970. His initial operational experience was as a B-57 Canberra pilot and instructor pilot. He was assigned to Holloman AFB, New Mexico; MacDill AFB, Florida; Ubon Royal Thai AFB, Thailand; Kadena Air Base, Japan; and Malmstrom AFB, Montana.

In 1975, Colonel Franck was assigned as the officer-in-charge of the Air Force Element, Joint Operational Control Center, Keflavik Naval Installation, Iceland. In 1976, he joined the staff at USAFA as an instructor and then as assistant professor in the Department of Economics, Geography and Management.

Colonel Franck reported to the Pentagon as staff analyst for bomber programs, the Office of the Assistant Secretary of Defense for Program Analysis and Evaluation in 1980. Colonel Franck returned to flying duties after his Washington, D.C. assignment and served as a flight commander following B-52 checkout. Later, he served on the operations staff of the 2d Bomb Wing, Barksdale AFB, Louisiana.

In 1985, Colonel Franck was assigned to Headquarters, Strategic Air Command, Offutt AFB, Nebraska, as deputy chief, Program Evaluation Division, and then as special assistant to the commander in chief, Strategic Air Command, where he served until his present assignment in 1989.

Executive Summary

This paper considers the question of cost and performance in major weapon systems. The existing state of technology determines what is possible in every new design. How much technology to incorporate into hardware involves choices between performance (better quality) and lower cost (greater numbers). Current design practices place a decided emphasis on performance.

An articulate group of critics with a large following charges that unchecked pursuit of technological opportunities precludes intelligent cost-performance choices. Weapon systems feature large numbers of expensive gadgets that add little to military effectiveness and much to cost. As a result, we're buying in numbers too small to be really effective. These issues were part of a major debate in the 1970s but faded somewhat with increased funding during the 1980s. With the drawdowns and reassessments of the 1990s, the question of numbers versus performance will likely return to prominence.

Chapter 1 is an overview of past experience in exploiting technology for military purposes. Traditionally, the slow pace of innovation and institutional conservatism made technology a minor part of the military planning problem. However, modern military powers specifically plan to advance military technology and exploit that progress with deployed hardware. The most radical practitioner of the modern approach is the United States, which regards technical superiority as a vital national interest.

Chapter 2 is a summary of the critics' views. Fundamentally, they assert that the acquisition process precludes systematic, rational choices between cost and performance. New weapons reflect the pursuit of technical opportunities rather than concern for military effectiveness. Study of the process itself underpins the critics' case. Although it is possible to find fault with what the critics say, it is difficult to defend the process itself. It is also important to remember that the critics' views are widely shared in the policy-making community.

Chapter 3 considers the empirical record and concludes that system designs show evidence of a consistent, rational pursuit of combat effectiveness. A set of 66 Navy and Air Force tactical aircraft types constitute the case study. The data reveal a military judgment that quality is more important than quantity, with that assessment consistently reflected in actual designs. The data do not support the critics' belief that increments in performance come at increasingly higher cost.

Chapter 4 looks at some indicators for the future. First, recent studies of actual combat results suggest that quality is indeed more important than quantity. Second is the effect of increased uncertainty. With a changing threat and planning environment, we no longer have a predominant scenario such as Central

Europe—therefore we have more uncertainty in our planning problem. Insights from the theory of financial portfolios suggest we should pay extra for assets that reduce risk in force performance. Some study evidence indicates that higher performance forces are less risky. Hence, there is reason to believe that continued emphasis on performance is appropriate in post-cold war system designs.

Chapter 1

Technology, Cost, and Performance as a Military Problem

THE purpose of this paper is to explore the issue of cost versus performance (or quality versus quantity) in major weapon systems. Every weapon design evolves within a given state of technology that provides a menu of technical options and associated costs. How much available technology to include in the design involves choices between more technology (higher performance) against lower cost (and greater numbers).[1]

Historical Record

THE relationship of technology to the other elements of the art of war and the exploitation of technical means in hardware design is not a new issue. The historical record indicates that technological innovation has exerted an important, and sometimes dominant, influence on military operations. However, history demonstrates that more technology does not always equate to greater operational effectiveness. Experience also shows that other factors have been major, sometimes dominant, influences as well.

Until the modern era, military technology progressed slowly. Before the twentieth century major military theorists could take technology as a given phenomenon, because it changed little in a lifetime.[2] It took nearly four centuries to fully realize the potential of gunpowder in terms of deployed hardware, doctrine, and tactics. Nearly one hundred years after demonstration of technical feasibility, a breech-loading infantry rifle first appeared as standard equipment.[3] Until the modern era, there was no defined process for advancing or exploiting technology for military purposes.[4] Inventions were perfected, deployed, and then forgotten.[5] Typically, innovations in hardware resulted from the efforts of individual inventors to find military customers.[6] In short, technical innovation was not the province of the military profession. Commentators from Sun Tzu to Clausewitz and Jomini could regard technology as essentially fixed, or at least as a matter outside their concern. Even some technically oriented theorists of the twentieth century such as J. F. C. Fuller and B. H. Liddell Hart emphasized the exploitation of particular technologies rather than technical progress as part of military planning.[7]

Traditionally, military institutions have been technically conservative, resistant to the incorporation of new technologies in hardware, and reluctant to reflect new technical means in doctrine, tactics, and force structure.[8] Technology was not a planning variable until well after the Napoleonic Wars. Trevor N. Dupuy credits the Prussian general staff of the nineteenth century as being the first to explicitly plan for technical innovations. Martin L. van Creveld emphasizes the influence of twentieth century warfare on military perceptions of technology.[9]

Changes in military technology have always exerted a pervasive influence on the conduct of war. Technology defines what is possible in military operations.[10] Even in ancient times, technical innovations or even a relatively small technical edge were extremely important. The Romans' incorporation of boarding ramps on galleys did much to wrest command of the sea from the Carthaginians in the Punic Wars. Similarly, Roman use of shock and fire weapons against the simpler, shock-oriented Hellenistic armies was a key ingredient in conquering the eastern Mediterranean.[11] Occasionally, there has been a decisive weapon for which the enemy had no counter, the Byzantines' "Greek fire" being a well-known example.[12] One can trace historical eras in military art and science through the use of such dominant weapons as the longbow, musket, and quick-firing artillery.[13] In 1945 Fuller equated victory with finding the right hardware.[14]

Nonetheless, technology has been only one of many factors in the military balance. Victory has always involved matching strengths against enemy weaknesses and masking deficiencies: more a matter of defeating an opponent than mastering nature. Many military revolutions did not involve technological innovation *per se* but rather the imaginative combination of existing means of war. The system growing out of the French Revolution and the genius of Napoléon is one example. The German army's introduction of the panzer division is another.[15]

Finally, exploiting technology is potentially dangerous. Periods of technical innovation have sometimes accompanied a deterioration in other military arts; a problem dating at least to the Hellenistic states of the ancient world.[16] Of even more concern is the tendency of factors other than military effectiveness to influence hardware design, such as the pursuit of technology for its own sake. Martin L. van Creveld's assessment of the engineers and designers of the Italian Renaissance is particularly interesting: "They applied their imaginations to the construction of a very large number of complicated machines, the real purpose of which was apparently not so much to do useful work as to explore ways in which those devices could be combined."[17]

Other dangers include technical innovations narrowly focused on established lines. The devices intended to keep the horse cavalry a viable combat arm after World War I are well-known examples of diverting technology (and investment) from the direct pursuit of military effectiveness.[18] Taking established lines of technology to extremes has resulted in warships so top-heavy with new devices that they sank on their maiden voyages or proved otherwise operationally ineffective. The extremely heavy plate of armor of the later medieval period is another example. That sort of innovation also concentrated fighting power in platforms so few and so precious that they could not be placed in harm's way, such as World War I dreadnoughts. A device that cannot be risked has only limited claims to being a weapon.[19]

Although military designs have always paid a premium for performance, it is not always clear how much is too much.[20] Airmen, in particular have disagreed. For example, Giulio Douhet advocated the "battleplane" (a moderate cost, moderate performance bomber), a view that contrasts with Air Marshal Hugh Trenchard's emphasis on weapons of first-rate quality.[21]

The Current Situation

In contrast to the military profession's traditionally passive attitude toward technology, all contemporary great powers have large and expensive military technical branches dedicated to advancing the state of the art and exploiting technical possibilities in weapon designs.[22] The clearest example of technical emphasis is the contemporary United States. The creation and exploitation of technical advantages is an integral part of contemporary national security strategy, and technical superiority is regarded as a major national interest.[23] A notable body of opinion and research holds that contemporary Western practice in system design is tilted almost exclusively toward the pursuit of technology without regard to cost.[24]

It is tempting to conclude that recent events in the Gulf war settled the argument in favor of the current emphasis on performance and quality. That may turn out to be true. The current generation of hardware has worked quite well.[25] And, it seems natural to conclude that the services have made good choices in hardware design.

To regard the debate on cost versus performance as permanently closed is more likely a misinterpretation of the lessons of Operation Desert Storm, future directions in military technology, the persistence of the critics, and the fiscal future. First, the stars of the Gulf operations were not just the high-cost, highly capable platforms such as the F-15 and F-117A. The new generation of precision guided munitions (PGM) recorded the most spectacular successes. Also, the A-10A, designed as a low-cost specialized aircraft, performed very well.[26]

The future direction of military technology will not necessarily favor the current emphasis on individual system performance. Even low-cost, perhaps unmanned, systems can carry highly sophisticated PGMs. In the air-to-air arena, the F-16's ability to carry the launch-and-leave advanced medium-range air-to-air missile (AMRAAM) may reduce differences in effectiveness with the F-15 and the advanced tactical fighter. AMRAAM may, in fact, tilt all-weather air-to-air combat results to favor the side with numbers. Advanced heat-seeking missiles caused similar results in close-in day visual flight rules (VFR) combat, as shown in the air combat evaluation/air intercept missile evaluation (ACEVAL/AIMVAL) test series.[27]

In a broader sense, the future of military technology appears to lie in the integrated battlefield, or, to use a Soviet term, in *reconnaissance strike complexes* (RUK).[28] Sensor complexes (satellites, reconnaissance [recce] aircraft, Airborne Warning and Control System [AWACS], and Joint Surveillance Target Attack Radar System [J-STARS]) quickly assess the operational situation. Modern communications rapidly link sensors, command centers, and combat units. PGMs are quickly and lethally allocated to enemy targets. The Desert Storm operation is possibly the first credibly operational RUK in actual combat.[29]

The implications of the integrated battlefield arguably include the potential for cheaper, less capable *systems* within the integrated *complex* (RUK). For example, central sensor systems plus communications could provide the situational awareness that we now expect from on-board components. The global positioning system (GPS) reduces the need for high-performance navigational systems aboard individual platforms. The critics are unlikely to miss these or similar arguments.

What's said here about RUKs is somewhat speculative. It is not speculative, however, to predict that defense needs will be underfunded in the years ahead—behavior fully consistent with past periods when no major military threat posed a clear and present danger to vital national interests. With appropriated funds never meeting planning forecasts, purchases of new equipment will be decreased, and force planning will suffer.[30] In those circumstances, design options that allow for larger numbers to be purchased will appear more attractive. And, a vocal group of advocates is in place to make the case to our national leadership.[31]

This discussion is therefore organized as part of an ongoing debate regarding cost and performance in major weapon systems. It begins with the critics' position, assesses the empirical record using cost and performance data for US tactical aircraft, and finally, offers some thoughts on cost and performance trade-offs in the post–cold war period.

Notes

1. J. F. C. Fuller, *Armament and History* (New York: Charles Scribner's Sons, 1945), 16; Thomas L. McNaugher, *New Weapons, Old Politics: America's Military Procurement Muddle* (Washington, D.C.: Brookings Institution, 1989), 6–8.
2. Martin L. van Creveld, *Technology and War: From 2000 B.C. to the Present* (New York: Free Press, 1989), 97, 219, 320–22.
3. Trevor N. Dupuy, *The Evolution of Weapons and Warfare* (New York: Da Capo, 1984), 291, 293.
4. Mary Kaldor, *The Baroque Arsenal* (New York: Hill and Wang, 1981), 11–12; Dupuy, 299, 300; McNaugher, 18; van Creveld, 278.
5. Fuller, 17, 27; van Creveld, 21.
6. Dupuy, 300; van Creveld, 219.
7. van Creveld, 320–22.
8. Fuller, 17; van Creveld, 219–20.
9. Dupuy, 306; van Creveld, 322–23.
10. van Creveld, 57.
11. van Creveld, 17–18, 59, 311.
12. Fuller, 61–62.
13. Dupuy, 290–98.
14. Fuller, 18, 19, 160.
15. van Creveld, 17, 19, 90, 167, 179–80, 316.
16. Fuller, 32–34.
17. van Creveld, 67, 70.
18. See Edward L. Katzenbach, Jr., "The Horse Cavalry in the Twentieth Century," *Public Policy*, vol. 7 (1958), in *American Defense Policy*, ed. John E. Endicott and Roy W. Stafford, Jr., 4th ed. (Baltimore: Johns Hopkins University Press, 1977), 369–70.
19. van Creveld, 69, 207, 318.
20. van Creveld, 54.
21. Giulio Douhet, *The Command of the Air*, trans. Dino Ferrari (London: Faber and Faber, 1927), 99–105; Hugh Trenchard, *Air Power and National Security* (London, 1946), 6.
22. Kaldor, 11–29; McNaugher, 1–16.
23. The importance of technology in national security strategy is found in a large number of policy statements, including Secretary of Defense Weinberger's competitive strategies initiative. See Caspar Weinberger, *Defense Report, FY87* (Washington, D.C.: Department of Defense, 1986), 86–88, 255–56; Dick Cheney, *Defense Report, FY92* (Washington, D.C.: Government Printing Office, 1991), ix, 43–45, 91–95; McNaugher, 1.
24. Kaldor and McNaugher already cited are representative. See chapter 2 for others.
25. Reported in news accounts and commentaries. See John T. Correll, "The Force at War," and James Canaan, "Airpower Opens the Fight," *Air Force Magazine* 74, no. 3 (March 1991): 6, 16–20; Stephen Budiansky and Bruce B. Auster, "A Force Reborn," and Michael Dugan, "First Lessons of Victory," *U.S. News & World Report* 110, no. 10 (18 March 1991): 30–36.
26. Dugan, 35–36.
27. For a favorable report on AMRAAM, see Jeffrey P. Rhodes, "The Next Round for Aerial Combat," *Air Force Magazine* 74, no. 2 (February 1991): 46–51. For a summary of the ACEVAL/AIMVAL controversies, see Walter Kross, *Military Reform: The High-Tech Debate in Tactical Air Forces* (Washington, D.C.: National Defense University Press, 1985), 84–85, 104–6.
28. van Creveld, 365–84.
29. Canaan, 17, 18; Dugan, 35.
30. McNaugher, 19, 135–37.
31. Kross, 201–4.

Chapter 2

The Conventional View of Cost-Performance Choices

THIS chapter could be titled "the gadget-happy military." The most commonly held belief (the "conventional wisdom") regarding quality versus quantity choices is that the major weapon systems are laden with technological bells and whistles that add much to cost but little, if anything, to military effectiveness. This is a summary of that position, without a complete survey or extensive critique.

The conventional wisdom position has an extraordinarily wide following. Advocates include an industrial leader like Norman Augustine, Washington analysts like William McNaugher and Chuck Spinney, as well as a more ideological critic like Mary Kaldor.[1]

One can simply state that military hardware is "gold plated" and not expect to offer much justification, even in the Pentagon. Asserting that military hardware is designed through conscious choices balancing increments in cost and performance in the interest of military effectiveness is likely to be controversial virtually anywhere. Therefore, whether or not one believes the critics, it is important to understand their positions.

The Flawed Process

THE conventional wisdom concerns itself with analyses of the acquisition process, with less attention to results. Procurement of military hardware serves at least three masters: technical, military, and political.[2] The process pursues at least three sets of inconsistent goals with the various players assessing different priorities.

Developing and producing military equipment has become routinized and bureaucratized. The industrial concerns involved constitute a remarkably stable group.[3] The major government players include the services (with using commands, research and development [R&D] agencies, and service staffs); the secretary of defense (and staff agencies); various (and increasingly numerous) congressional committees, subcommittees, and support agencies (including the General Accounting Office, the Congressional Budget Office, and the Congressional Research Service); and (more recently) the Joint Staff.[4]

Each agency has its own agenda and many avenues to pursue it. A player that has lost in one forum may "appeal" to others, including the federal courts and the press. The multiplicity of interested parties, objectives, and decision arenas encourages contentious and strategic behavior; most agree that the process is adversarial.[5]

The process itself, therefore, obscures the question of whether we are designing and fielding cost-effective military equipment. No one takes specific exception to cost-effectiveness, but it is only one of many objectives those involved pursue.

The Technological Imperative

THE United States is committed to superiority in both basic military technologies and fielded systems—for good reason.[6] We have a competitive advantage in our ability to develop sophisticated, high-performance weapon systems. We compensate for our unwillingness to put large numbers of people in harm's way and accepting large numbers of casualties with advantages in technology. We think in terms of fighting outnumbered.

The conventional wisdom charges that we've taken emphasis on technology to extremes. We add gadgets that are unrelated to military effectiveness for reasons endemic to the way we do business.[7] Typically, we buy new systems as technical improvements instead of replacing worn-out equipment. More than one industrial concern is able to develop and *manufacture equipment* embodying the new technologies. Therefore, contractor competition emphasizes technical features, with optimistic promises about costs and risks.[8]

Officials, military and civilian, most directly involved with the new system preserve that optimism. Beyond the enthusiasm normal to the early stages of any new project, they have a firm belief in the military efficacy of the technologies being pursued. And, as practiced bureaucrats, they know what it takes to form the coalitions needed to sustain the program throughout the protracted development and production process.[9] They are aware of the importance of a consensus among interests and constituencies within one's service, in Department of Defense (DOD), and on Capitol Hill.

Building coalitions inevitably requires compromise, often in the form of adding someone else's favorite gadget to the system specifications.[10] In the optimism of the early stages, that is easy to do. Therefore, new systems inherently start with overspecified requirements (burden of consensus) and too little funding (burden of optimism).[11]

To make matters worse, the new system is rushed toward production, minimizing the time available to test the design's practicality and to correct flaws at a modest cost. This practice makes eminently good sense to the players involved. Technology inevitably diffuses and a nation committed to technical superiority cannot afford to dither about exploiting its technical advantages. Moreover, the sooner the system reaches production and deployment, the less time the supporting coalition needs to hold together.[12]

The process therefore dictates that development and procurement of military hardware proceed with little or no reference to the cost-quality trade-offs. The combined burdens of consensus, optimism, and overspecification mean gadgets added for reasons unrelated to operational utility.

Technology versus Innovation and Effectiveness

THE quest for technology is not the same as a commitment to innovation. In fact, the acquisition establishment often opposes true innovation. After the start of development, the contractor must work within an extensive list of "requirements," many of which preclude new means of designing and producing an effective military system.[13] Coalition building requires incorporating established mature technologies with the bureaucratic support. Radically new technologies tend not to have strong backers and are therefore written out of the system specifications.[14]

As a result, we demand large improvements in performance, and we rely on mature (some say "decadent") technologies, from which increments of performance are available only at very high cost.[15] Facing sharply restricted technical choices and expected to live within optimistic cost estimates, the contractors and program managers inevitably devote most of their efforts to satisfying the performance goals.[16] However, there is no free lunch; the costs associated with the technological imperative are increased complexity, lower reliability, high maintenance costs, and inadequate numbers of weapons purchased.[17]

Gadgets specified at conception plus other gadgets added during development make our weapon systems highly complex—the "baroque" arsenal.[18] In operational use, complex systems are likely to break, are difficult to repair, and generally expensive to maintain. They are inherently unready for combat.[19]

Therefore, the quest for performance is not consistent with designing for military effectiveness. Some critics charge that the performance increments are not worth the extra costs. Some go further and assert that extra complexity actually reduces the effectiveness of individual units.[20]

The conventional wisdom concludes the acquisition process works badly. The most noteworthy successes occur outside the usual channels. The critics state, for example, that we have the F-16 only because DOD leadership did not follow established Air Force procedures.[21]

A Preliminary Assessment

ONE can find fault with the conventional wisdom. First, the critics haven't always been careful with their arguments. When it comes to specific cases, what constitutes a gold-plated, baroque design is often vague, or at least subject to differing interpretations. For example, Kaldor cites the inability of Pakistani F-104s to effectively engage low-altitude, subsonic Indian aircraft (Gnats) in 1965 as clear-cut evidence of the deficient performance of high-performance, multimission, baroque weapons.[22] Actually, there is a strong case for the F-104 not being a multimission aircraft. The original design envisioned a high-altitude, supersonic interceptor. A baroque system would have included lower altitude engagements in its specifications and would have performed better against the Indian aircraft.[23]

Likewise the issue of gold plating and complexity is clouded in the case of the F-86—the favorite of many critics who cite its conspicuous successes in Korea and in the 1971 war between India and Pakistan and tout it as the "last great fighter built by the United States."[24] However, added gadgets, complexity, growth in gross weight, and low availability for combat plagued the F-86 in its early years.[25] It appears that the critics' good examples share the problems of their bad examples.

Murray L. Weidenbaum uses external equipment cluttering clean aerodynamic designs as proof of gold plating.[26] Actually, most external equipment is added as part of modifying equipment in service—something most critics assert is not done often enough.[27]

The story sometimes does not track well. For example, Kaldor takes pains to differentiate the Soviets' "conservative" approach to weapon design with the baroque Western approach.[28] Since Western methods are argued to lessen military effectiveness, one would expect the Soviets to be ahead in the military competition. Instead, Kaldor states that the West has consistently held the initiative in the arms race—with the Soviets doggedly trying to keep pace.[29] It is difficult to reconcile those two assertions, especially when offered together.

Second, experience disproves many propositions the critics offer. Kaldor predicted in 1981 that electronic innovations (e.g., PGMs) would receive insufficient attention because of preoccupation with the older (decadent) technologies associated with the aircraft and automotive industries.[30] That statement is at odds with McNaugher's well-documented contention that the services pursued the Maverick (a PGM by any definition) with too much enthusiasm and haste.[31]

Another example is Spinney's prediction that fighters like the F-15 simply can't generate sorties in anything resembling the amounts predicted in war plans.[32] Field tests with F-15s have demonstrated ability to meet or exceed the sortie rates specified in the war plans. Similar results occurred in the Gulf war.[33]

Conclusions Regarding the Conventional Wisdom

THERE are three keys to understanding the conventional wisdom. First, it is well entrenched in popular beliefs. Most people believe that military hardware is developed and procured without regard to cost, that gold plating is simply a part of the way the military works. Second, the critics are not perfect. Many parts of their arguments do not withstand close examination. Finally, even with imperfections, it is difficult to comprehensively refute the conventional wisdom. The critics aim most of their fire at the acquisition process. Taking them on point by point means defending an imperfect process, which most agree is not defensible in every detail.

Notes

1. Norman R. Augustine, *Augustine's Laws* (New York: Viking Penguin, 1987); Mary Kaldor, *The Baroque Arsenal* (New York: Hill and Wang, 1981); Thomas L. McNaugher, *New Weapons, Old Politics: America's Military Procurement Muddle* (Washington, D.C.: Brookings Institution, 1989); Franklin C. Spinney, *Defense Facts of Life: The Plans/Reality Mismatch* (Boulder, Colo.: Westview Press, 1985).

2. McNaugher, ix, 3, 13, 48, 121, 148.

3. Kaldor, 18, 61–62, 75-76, 170; McNaugher, 150–51.

4. McNaugher, 2, 10–12.

5. Ibid., 10–[illegible], 148.

6. Walter Kross, *Military Reform: The High-Tech Debate in Tactical Air Forces* (Washington, D.C.: National Defense University Press, 1985), 118–20; McNaugher, 1–3, 87.

7. Kaldor, 5, 21, 75; McNaugher, 125–26; Spinney, 98, 110.

8. Kaldor, 67–68, 71; McNaugher, 132, 153, 155, 179; Spinney, 144–45, 162.

9. Augustine, 265–73; McNaugher, 13, 121; Spinney, 107.

10. McNaugher, 13, 125–28.

11. Augustine, 267–73; McNaugher, 126–27.

12. McNaugher, 87, 107.

13. Augustine, 132; Kaldor, 170–71; McNaugher, 107.

14. McNaugher, 2, 87, 109, 128.

15. Augustine, 130–38; Kaldor, 18–24; McNaugher, 88–92.

16. McNaugher, 127.

17. Kaldor, 25–26; McNaugher, 107, 109–12, 135–39; Spinney, 29–32, 51.

18. Kaldor, 18–22, 25; Spinney, 84–89.

19. Augustine, 156–58; Kaldor, 25-26, 176–79; Spinney, 32–38.

20. Kaldor, 26; McNaugher, 107-9; Spinney, 82–104.

21. McNaugher, 77, 137.

22. Kaldor, 164.

23. The F-104 was designed to take off and climb quickly to high altitude and engage targets in that regime. It was designed to be a lightweight, specialized, relatively inexpensive aircraft. As the aircraft designer, Kelly Johnson, put it: "What we have done is bring an end to the trend toward constantly bigger, constantly more complicated, constantly more expensive airplanes." The Air Force originally wanted a more expensive, more versatile delta-wing design. Thus, the F-104 design was a turn away from increasing complexity and the "baroque arsenal." A delta-wing aircraft would have done much better than the F-104 (with its very high-wing loading) against subsonic, low-altitude, maneuvering targets. The only tenable conclusion is that the failure Kaldor cites (note 22) resulted from not pursuing a baroque system. See Marcelle Size Knaack, *Encyclopedia of U.S. Air Force Aircraft and Missile Systems*, vol. 1, *Post-World War Two Fighters 1945–1973* (Washington, D.C.: Office of Air Force History, 1978), 175.

24. Briefing, Pierre Sprey, cited in Kross, 90, 218; Spinney, 84.

25. Knaack, 55, 58, 175.

26. Murray L. Weidenbaum, *The Economics of Peacetime Defense* (New York: Praeger, 1974), 59-61.

27. Kaldor, 83-86, 96; McNaugher, 118-21.

28. Kaldor, 100-24.

29. Kaldor, 107-10.

30. Ibid., 36-37, 173-74, 230.

31. McNaugher, 93-94, 200.

32. Spinney, 38-46.

33. Jeffrey P. Rhodes, "Eagles 17, Bean Counters 4," *Air Force Magazine* (April 1988): 74, 76; James F. Canaan, "Airpower Opens the Fight," *Air Force Magazine* 74, no. 3 (March 1991): 16-20.

Chapter 3

The Empirical Record

The Case of US Tactical Air

THE proof is in the pudding, and the worth is in the output. Although much attention has been devoted to flaws in the acquisition process, the conventional wisdom has committed less effort to assessing the outcomes. This chapter uses US tactical air as a case study to assess the outcome of the acquisition process.

Unit costs of major weapon systems have increased—a well-publicized and acknowledged fact. The performance and combat capabilities of major weapon systems have also increased, a fact less publicized and acknowledged. Two examples illustrate the latter point. One squadron of F-15s could easily have replaced the entire bomber force committed against Schweinfurt in October 1943—penetrating contemporary air defenses, achieving the same level of damage, and taking fewer casualties.[1] Maj Gen Haywood S. Hansell (who did much to formulate the strategic bombing campaigns of World War II) stated that one contemporary heavy bomber (B-1 or B-2) is worth more than one hundred heavy bombers of World War II vintage, even against modern air defenses.[2]

Many who hold to the conventional wisdom would not disagree fundamentally with those estimates of capability increase. They would assert that increases in performance reflect pursuit of technological possibilities without consideration of the cost implications.

Fortunately, the question of what, if any, cost-performance trade-offs affect system designs is amenable to some empirical verification. The Analytic Sciences Corporation (TASC) has developed an extensive data base relating mission capability to cost of US tactical aircraft.[3] A Rand analysis of that data has shed considerable light on the factors accounting for cost of tactical aircraft.[4] Building on those studies, we can subject various propositions about major weapon system cost and performance to empirical test—using US tactical aircraft as a case for study.

Empirical Implications of the Conventional Wisdom

REFERRING back to chapter 2, we can state several empirical propositions consistent with the conventional wisdom.

1. Unit cost is growing rapidly in real terms, even after lower production rates are taken into account.[5]

2. The pursuit of higher performance has led to fewer aircraft being produced.[6]

3. We are thoroughly locked into mature, "decadent" technologies; that is, cost, performance, and numbers of missions are growing over time.[7]

4. Increased performance comes at a very high cost.[8]

5. Performance requirements are pushed to the edge of currently available technology. There is no systematic trade-off between performance and cost; complexity and "gold plating" are increasing.[9]

The first three propositions can be examined readily with the available data.

Proving or disproving proposition 4 requires a model to account for the cost of tactical aircraft. Proposition 5 is the most serious indictment of current practices and is the centerpiece of the conventional wisdom. Examination of this last proposition requires a model for analyzing cost-performance trade-offs.

This section first examines propositions 1 through 3. Next, it provides an explanatory model to account for aircraft cost that serves as a means to evaluate proposition 4. A rational design model is then offered as a benchmark for examining actual cost-performance trade-offs. Taken together, the empirical and rational design models provide a means for assessing the merits of proposition 5.

Trends in Tactical Aircraft Cost and Performance

PROPOSITION 1 asserts a clear trend toward increasing costs in major weapon systems. Jacques Gansler puts the increase at 5 to 7 percent per year, even after taking inflation and production rates into account.[10] At face value, tactical aircraft data supports Gansler's statement. If we exclude the effects of production rate, we note then real unit cost has grown at approximately 6 percent per year.[11] Figure 1 plots real unit cost (corrected for production rates) with respect to time. However, if we also correct for the effects of performance, then the time trend disappears—which casts considerable doubt on the significance of Gansler's statement.[12] This is evident in figure 2.

Proposition 2 states that production rates have decreased over time, with the pursuit of higher performance being a key factor. The empirical evidence supports that hypothesis. In fact, there is a clear downward trend over time, even after the effects of wars (Korean and Vietnam) and performance have been included, as figure 3 shows.[13]

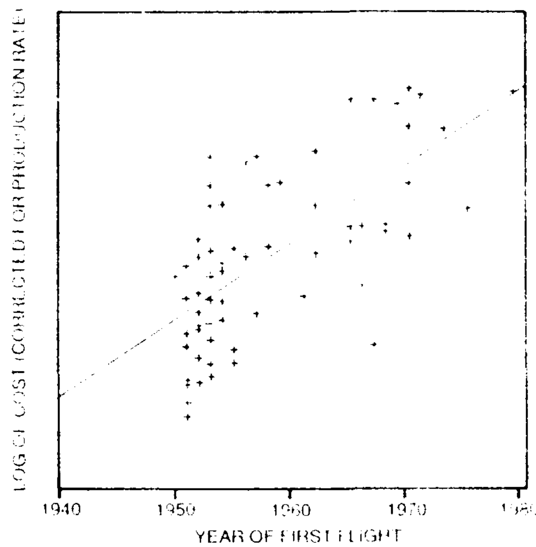

Figure 1

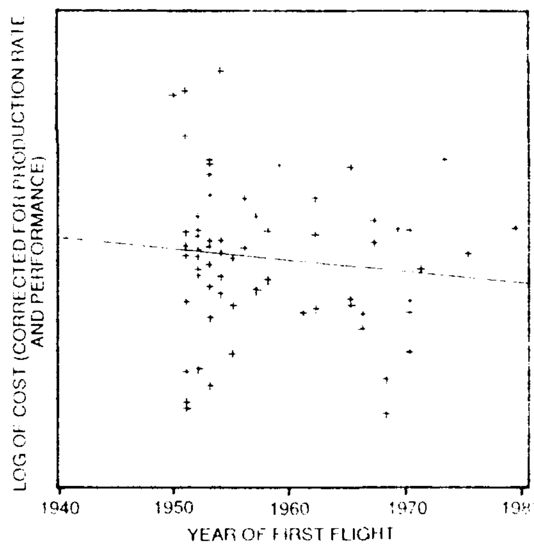

Figure 2

Commitment to mature technologies means pursuit of ever-higher performance and multimission capabilities despite very high costs, and the increasingly higher cost of more performance.[14] Proposition 3 therefore asserts that we observe higher performance, higher cost, and greater tendency to multimission designs. Virtually all observers would agree with the higher costs and capabilities over time. There is also some evidence for designing more missions into tactical aircraft, as shown in figure 4.

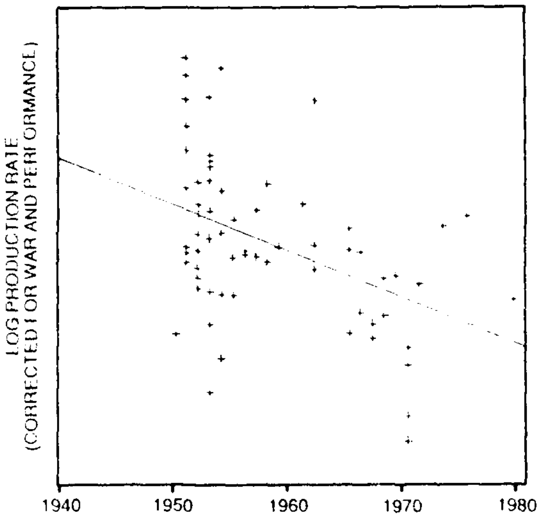

Figure 3

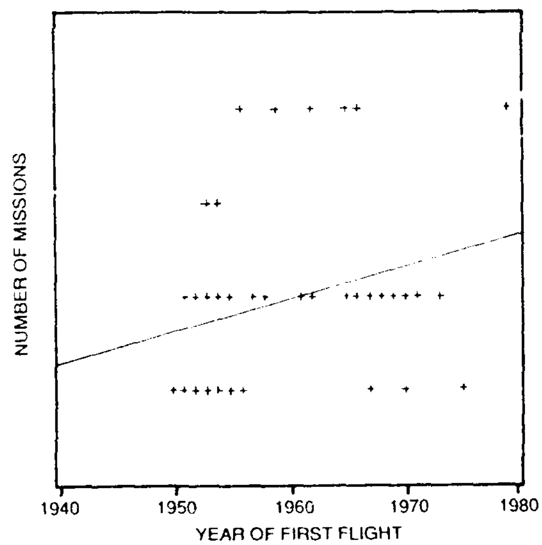

Figure 4

Accounting for Tactical Fighter Costs

THE work of Gregory C. Hildebrandt and Man-bing Sze provides the basis for explaining tactical fighter costs—using the TASC data and taking into account conditions of production (to include costs of materials and learning curves), performance, and mission design.[15] The following model explains tactical aircraft cost:

$$C = \underset{(-.08)}{.959}\ [q^{\underset{(13.65)}{(1.365)}}]\ [e^{\underset{(-2.93)}{(-.374MOD)}}]\ [RATE^{\underset{(-2.92)}{(-.233)}}]$$

$$[e^{\underset{(2.85)}{(.345AI)}}]\ [e^{(-.03t)}] \qquad (3.1)$$

$$R^2_{adj} = .85,$$

where C is real unit cost (in millions of fiscal year 1981 dollars), q is performance as measured by the TASC methodology, R is production rate, MOD and AI are dummy variables (taking on the value one for modified aircraft and interceptors, respectively). The effect of time (t) starting at 1950 (where $t = 1$) is estimated exogenously, using the Hildebrandt and Sze estimate of technical progress.[16] All estimated coefficients are statistically significant except the constant.

Using the empirical model, we can now comment on proposition 4. Norman R. Augustine asserts that the last 10 percent in performance accounts for about one-third of the cost; Walter Kross quotes the critics as stating the last 10 percent accounts for about half of total cost.[17] According to model (3.1), we would expect the last 10 percent of performance to account for approximately 13 percent of total cost,[18] much less than the amounts the critics have claimed.

A Rational Choice Model of Cost-Performance Trade-offs

INHERENT in any system design is a trade-off between performance and cost. The opportunity cost of better performance is the added quantity possible with a cheaper, less capable design. Also, combat effectiveness is a function of both quantities available and capabilities of each unit.[19] A military service interested only in maximizing capabilities would trade off performance against cost to formulate the design that provides the largest amount of capability for a given budget.[20] The design problem is depicted graphically in figure 5. At any given level of technology, T, performance comes at a price described by the performance-cost frontier, AA.[21] Therefore, the service faces the choice between fewer but more capable aircraft, or more numerous but less capable aircraft, as depicted in figure 6. The curve BB represents budget constraint of the form

$$B = [C(q)]\,[x],$$

where C is average unit cost as a function of performance (q) and x is number procured. The curve BB′ represents an increase in available resources. The curve EE represents combinations of performance and quantity that result in equal levels of effectiveness (an isoquant): FF represents an increase in effectiveness, while DD constitutes a decrease. The optimum design, q^*, occurs at a point of tangency between the isoquant, EE, and the budget constraint, BB. At that point, the slope of the budget line is equal to the slope of the isoquant.

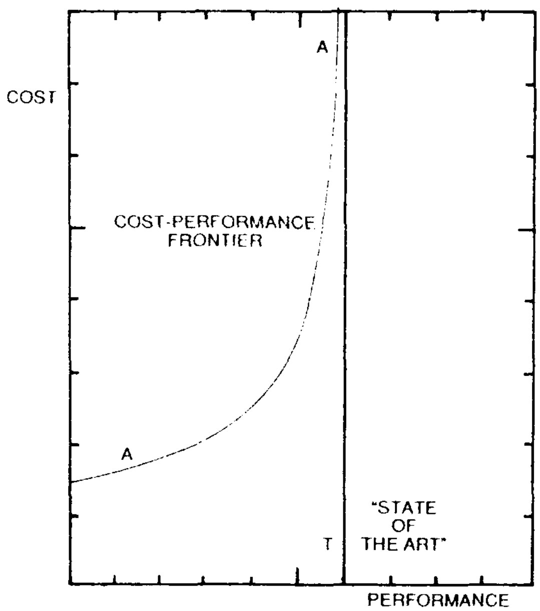

Figure 5

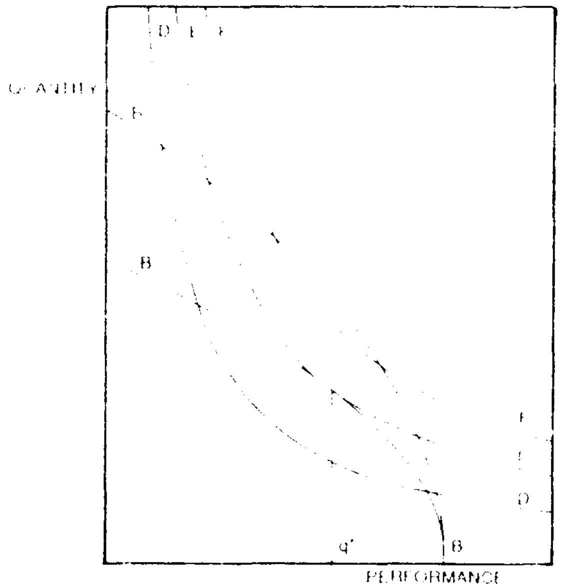

Figure 6

The implications of tangency are important. Suppose, as Frederick L. Frostic and others state, that combat effectiveness is a multiplicative relationship of quantity available and individual system capabilities, such as,

$$R = q^{a}\,x,$$

where R is effectiveness, q is performance, and x is number available.[22] The slope of the isoquant is

$$dq/dx = -\,q/ax.$$

Likewise, the slope of the budget line is

$$dq/dx = -\,C/C_q x,$$

where C_q is the first partial derivative of C with respect to q. Since the slopes are equal, then

$$qC_q/C = a.^{23} \qquad (3.2)$$

Equation (3.2) characterizes a rational design that balances performance against cost to obtain the greatest possible combat capability. As already shown in the empirical model, we can relate performance and cost as follows (if all other variables are held constant):

$$C = [S_0]\,[q^{S1}]:$$

where S_0 includes the (constant) values of all variables except q. We can then relate the empirical model (3.1) to the rational design model:

$$qC_q/C = [qS_0S_1q^{(S_1-1)}]/[S_0q^{(S_1)}],$$

$$\text{or, } qC_q/C = S_1 \qquad (3.3)$$

Combining (3.2) and (3.3) gives us

$$S_1 = a. \qquad (3.4)$$

Equation (3.4) provides a crucial insight. Rational choice in systems design means that the assessed relative importance of performance and numbers is revealed in the parameter S_1, which can be empirically estimated. This suggests two observations. First, since $S_1>1$, the empirical record shows a clear preference for performance over quantity.[24] Second, we can formulate an alternative hypothesis to proposition 5.

5.a. Tactical aircraft designs reflect a systematic and consistent trade-off between performance and cost.

If true, proposition 5.a falsifies 5. If proposition 5.a were not true, we would expect to find the estimated parameters of model (3.1) to be of doubtful significance. We would also expect to find the overall model to be of dubious value in explaining cost variances.[25] If, as proposition 5 asserts, weapon system designs are becoming increasingly baroque or gold plated, we would expect to find some evidence of changes in behavior over time, with the estimated value for S_1 increasing.[26] There is good evidence of a change in the overall model taking place for designs that first flew in 1957 or later; the model applied to the two subsets gives results as follows:

first flight before 1957,

$$C = \underset{(-.13)}{.907}\ \underset{(5.69)}{[q^{(1.158)}]}\ \underset{(-1.08)}{[e^{(-.287MOD)}]}\ \underset{(-1.62)}{[RATE^{(-.178)}]}$$

$$\underset{(2.37)}{[e^{(.414AB)}]}\ [e^{.03t}] \qquad R^2_{adj} = .59;$$

first flight 1957 or after,

$$C = \underset{(1.50)}{2.114}\ \underset{(11.48)}{[q^{(1.102)}]}\ \underset{(-7.12)}{[e^{(-.678MOD)}]}\ \underset{(-2.38)}{[RATE^{(-.198)}]}$$

$$\underset{(3.26)}{[e^{(.270AB)}]}\ [e^{.03t}] \qquad R^2_{adj} = .93.$$

Analysis of the data indicates that observed preference for performance has not changed over time.[27] In short, the empirical record for tactical aircraft is consistent with the rational choice model.

Assessment of the Empirical Record

Two findings are by far the most interesting and important. First, the services have clearly favored performance over quantity; or, restated in terms of the rational design model, the services have revealed an assessment showing performance to be more important than numbers in tactical air combat. Second, observed behavior is consistent with the rational design model: there is strong evidence to support the proposition (5.a) that system designs consistently reflect an assessment of the roles of system performance and numbers in producing combat effectiveness.

The second finding provides a new perspective for viewing the conventional wisdom (especially in propositions 1–4). The critics appear to be reasonably accurate observers, but not profound analysts. In fact, the more damning the assertion offered, the less the empirical record supports it. Propositions 1, 2, and 3 are factual, although the conclusions drawn are sensitive to the inclusion of other explanatory variables beyond the simple passage of time.

Proposition 4 is, at minimum, an exaggeration. Increased performance does indeed carry a price tag; but, it is far less than asserted. Finally, if one accepts proposition 5.a, then propositions 1–4 fail the "so what" test. Higher performance (along with higher costs and lower numbers) is justified based on military calculations of combat effectiveness.[28]

So, what are the real issues? First is military competence and integrity. The performance measures used rely heavily on professional military judgments.[29] Paid consultants to the DOD (a significant number of whom are retired officers) compiled all the data used here. Although there appears to be no ulterior objectives in the work cited, those determined to distrust the military or deprecate military expertise will distrust or deprecate the analysis presented. Second is the real importance of system performance versus numbers in determining military effectiveness. Though the military has shown a consistent assessment in favor of performance, many would argue that numbers are more important. Some cite the ACEVAL/AIMVAL test series as proof of the greater effectiveness of larger numbers of cheaper, simpler air-to-air fighters.[30] Likewise, the importance of a regular "presence" over the battlefield (achievable through large numbers) has been used to support the contention that numbers are also more important in air-to-ground missions.[31]

Notes

1. Briefing, Headquarters TAC, "Combat Capability Comparisons," undated.

2. Maj Gen Haywood S. Hansell, Jr., and Col H. S. Hansell III, "Air Power in National Strategy," Top Secret, 1988. It seems significant that neither this nor the previous reference (note 1) has received general publication.

3. Edward Timberlake et al., *The TASCFORM-AIR Model: Vol I - Methodology Development*, technical report (TR)-1334-3 (Arlington, Va.: TASC, 1980); Jonathan M. Regan and William J. Vogt, *The TASCFORM Methodology*, 3d ed., TR-5192-1-2 (Arlington, Va.: TASC, 1988); William E. Dupuy, Jr., et al., *U.S. Military Aircraft Cost Handbook*, TR-8203-1 (Falls Church, Va.: Management Consulting and Research, Inc., 1983).

4. The sample studied was 66 Navy and Air Force fixed-wing tactical aircraft. First flights range from 1950 (F-89) to 1979 (F-18). Gregory G. Hildebrandt and Man-bing Sze, *Accounting for the Cost of Tactical Aircraft*, Rand Report N-2420-PA&E (Santa Monica, Calif.: Rand Corp., 1986), 1–2, 44–45.

5. Jacques Gansler, *Affording Defense* (Cambridge, Mass.: MIT Press, 1989), 7; Thomas L. McNaugher, *New Weapons, Old Politics: America's Military Procurement Muddle* (Washington, D.C.: Brookings Institution, 1989), 168.

6. McNaugher, 87–122.

7. Mary Kaldor, *The Baroque Arsenal* (New York: Hill and Wang, 1981), 20, 22; McNaugher, 88–92.

8. Norman R. Augustine, *Augustine's Laws* (New York: Viking Penguin, 1987), 138; Walter Kross, *Military Reform: The High-Tech Debate in Tactical Air Forces* (Washington, D.C.: National Defense University Press, 1985), 63.

9. McNaugher, 90, 135–37; Kaldor, 22, 24, 26.

10. Gansler, 7.

11. Taken as a deterministic statement, proposition 1 is of the form:

$$C = C_O\,[T^m]\,[R^n],$$

where C is real cost per unit, C_O is a constant, T is time and R is production rate. The parameter m is expected to be positive and n negative.

If we define C as the average cost of the first one hundred units in millions of fiscal year 81 dollars (as is done in the TASC data), let T be the year of first flight of the system, and let $T = 1$ at 1950, then the fitted equation is as follows:

$$C = \underset{(3.21)}{9.38}\,[\underset{(3.93)}{T^{.058}}]\,[\underset{(-2.33)}{R^{(-.317)}}],$$

$$R^2_{adj} = .42.$$

The t-statistics for the estimated parameters are stated in parentheses below each. All parameters are significantly different from zero.

12. If we modify the model in note 11 to also correct for increased performance, the fitted equation becomes

$$C = \underset{(-.84)}{-.478}\,[\underset{(-.62)}{T^{(-.008)}}]\,[\underset{(-1.34)}{R^{(-.124)}}]\,[\underset{(9.11)}{q^{(1.232)}}]$$

$$R^2_{adj} = .75$$

Only the estimated parameter for performance (q) is statistically significant. Though the apparent trend is negative, the slope is not significantly different from zero.

13. Proposition 3 can be stated mathematically as follows:

$$R = C_O\,[T^c]\,[e^{(b*WAR)}]\,[q^f].$$

where WAR is a dummy variable (and takes on the value of one for systems introduced in war years and zero otherwise). The fitted equation is

$$R = 5.419\,[T^{(.041)}]\,[e^{(.385 * WAR)}]\,[q^{(.279)}]$$
$$(17.57) \quad (-2.69) \quad (2.36) \quad (-1.59)$$

$$R^2_{adj} = .40$$

All estimated parameters are statistically significant except for performance, q.

14. Kaldor, 5, 19–22, 25, 97, 112. In the TASC methodology, fixed-wing aircraft may have one to four missions (close air support, interdiction, fighter, interceptor, or various combinations). Timberlake, 2-2 to 2-4.

15. Hildebrandt and Sze, 15, 18, 35.

16. Ibid., 18, 35. The results seen here are consistent with the alternate formulation, which also uses the TASC performance measure. Better results came from the dummy variable AI (interceptor) instead of ATTACK (accounting for aircraft with air-ground missions only).

17. Augustine, 138; Kross, 63.

18. Hildebrandt and Sze reach a similar conclusion. See Hildebrandt and Sze, 35. Suppose we observe a performance level of 10 at a cost of $10 million. Everything else being equal (including technology), if performance were 9 instead of 10, estimated cost would then be reduced to about $8.7 million:

$$C(9)/C(10) = [9^{1.365}]/[10^{1.365}] = .866.$$

19. Frederick L. Frostic, "Quality Versus Quantity in Tactical Fighter Forces," *Journal of Defense Research* 13 (1981): Declassified 1987, 286.

20. Actually, this is a necessary condition for optimum system design. Rogerson states more general conditions. See William P. Rogerson, "Quality vs. Quantity in Military Procurement," *American Economic Review* 80 (1990): 84–85.

21. The basic form of the curve in figure 5 comes from Leonard Sullivan, as discussed in McNaugher. In Sullivan's formulation, the cost-performance frontier goes asymptotic at performance level T. See McNaugher, 6–7.

22. Frostic, 286.

23. Since, by definition, effectiveness is constant along the curve EE, then

$$dE = 0 = E_q dq + E_x dx = aq^{(a-1)}x dq + q^a b dx,$$

which can be simplified as

$$dq/dx = -q/ax.$$

Likewise, cost is constant along the curve BB; that is,

$$dB = 0 = C_q x dq + C dx,$$

or

$$dq/dx = -C/C_q x.$$

Continuing,

$$-C/C_q x = dq/dx = -q/ax,$$

or, simplifying,

$$qC_q/C = a.$$

In more technical terms, the left-hand side of this last equation is the elasticity of unit cost with respect to performance. The right-hand side of the equation is a measure of the relative importance of performance in overall force effectiveness—being the quotient of the elasticity of effectiveness with respect to performance divided by the elasticity of effectiveness with respect to quantity.

24. A standard t-test shows that S_1 is significantly greater than one. Since $S_1 = a/b$ in the rational choice model, then we can be confident that the empirical data reveals that $a > b$; that is, that system performance is more important than numbers in producing effectiveness.

25. Using standard regression analysis, we wouldn't expect the estimated parameters to be significantly different from zero, nor the overall model to explain cost variation very well. In fact, parameter estimates are highly significant, and the model does account for costs well.

26. One can look for such changes by testing for the presence of changes (or "breaks") in the parameters of the model: at any given time period using the Chow Test, or, in the absence of prior information, estimate the most likely breakpoint using the Quandt Maximum Likelihood Estimator. In this particular case, the maximum likelihood estimate of a break occurs at 1957; it turns out that this is the only period for which the Chow Test is significant. See Franklin M. Fisher, "Tests of Equality between Sets of Coefficients in Two Linear Regressions," *Econometrica* 38 (1970): 361–66. S. M. Goldfeld and R. E. Quandt, *Nonlinear Methods in Econometrics* (London: North-Holland, 1972), 258–62.

27. In fact, there is weak evidence for a *decrease* in S_1.

28. A convinced critic could argue that all this section has really done is fail to disprove proposition 5.a. A rejoinder would be in two parts: (1) Failure to find a significant and positive trend in costs not accounted for by other variables casts considerable doubt on proposition 5. (2) Since the services have the highest degree of professional background in judging military effectiveness (and whose members face some possibility of living or dying based on the accuracy of those assessments), there is at least some burden of proof on those who would criticize. Moreover, the acquisition process is, in fact, no more flawed than its products.

29. Timberlake, 1-5 to 1-7, Appendixes A and B.

30. Kross, 91; Rogerson, 83.

31. Franklin C. Spinney, *Defense Facts of Life: The Plans/Reality Mismatch* (Boulder, Colo.: Westview Press, 1985), 89.

Chapter 4

Cost-Performance Choices in the Future

TO ensure that we field cost-effective hardware in the fiscally constrained years ahead, it is useful to think through the Air Force approach to quality-quantity trade-offs. At minimum, it is highly advantageous to better articulate the reasons for current practices. Chapter 2 indicated some difficulty discerning where those trade-offs are actually made in the acquisition process. However, chapter 3 showed substantial evidence for major weapon system designs following a consistent, rational pattern of cost-performance trade-offs. This chapter addresses two issues. First, does the empirical evidence support past assessments of performance being more important than quantity? Some evidence based on Lanchestrian models of combat results supports the assessment that quality is more important than numbers.[1] Second, with the Central Front contingency no longer dominating defense planning, how will the quantity-performance issue play out in a world of multiple and uncertain contingencies?[2] Portfolio theory provides interesting insights, with indications that we should continue emphasis on performance in the future.

Relative Importance of Quality and Quantity in Combat

CHAPTER 3 discussed multiplicative effectiveness measures of the form

$$R = q^a x. \qquad (4.1)$$

where R is combat capability, q is system performance, x is numbers available, and a is the relative importance of quality versus quantity in combat. Just as available evidence reveals the *assessed* importance of performance versus quantity, historical data provides estimates of their *actual* importance. A number of empirical studies based on Frederick W. Lanchester's model of combat consider combat results as a function of quality and quantity of forces engaged. Lanchester was first to organize the performance-quantity issue within a defined analytical framework, and to propose a measure of force effectiveness. The original formulation assumed loss rate at any instant is based on opposing force size and performance of each unit; that is,

$$dx/dt = -q_y\, y$$
$$dy/dt = -q_x\, x, \qquad (4.2)$$

where x and y are force levels and the q's are positive constants reflecting performance of individual units.

System (4.2) can be solved for

$$(x_0^2 - x^2) / (y_0^2 - y^2) = q_y / q_x \qquad (4.3)$$

where x_0 and y_0 are the force sizes at the start of the engagement. As is evident in (4.3), the *squares* of the force sizes reduce at the relative rate of (q_y/q_x). Therefore, numbers are more important than performance in this particular model. For example, if the X side were twice as numerous as the Y, then Y would need four times the performance of X to have the same combat capability. Lanchester proposed his famous quantity-squared measure of effectiveness: "The fighting strength of a force may be broadly defined as proportional to the square of its numerical strength multiplied by the fighting value of its individual units."[3] Mathematically, we can state the square law as equating fighting strength to $[q_x x^2]$. In terms of equation (4.1), we can write

$$R = q^{(.5)} x. ^{4} \qquad (4.4)$$

James G. Taylor, D. S. Hartley, and others have generalized Lanchester's equations (4.2) to the form

$$dx/dt = -q_y x^s y,$$
$$dy/dt = -q_x y^s x. \qquad (4.5)$$

where s is a positive constant.[5] System (4.5) can be solved for

$$(x_0^{[2-s]} - x^{[2-s]}) / (y_0^{[2-s]} - y^{[2-s]}) = q_y/q_x. \qquad (4.6)$$

Then, Lanchester's original effectiveness measure (4.4) can be generalized to

$$R_x = q_x^{[1/(2-s)]} x. ^{6}$$

Present studies identify three discrete cases defined by the value of s:

- if $s = 0$, we have Lanchester's original model, the square effectiveness measure applies, and numbers are important;
- if $s = 1$, a similar measure of effectiveness applies, and effectiveness is proportional to quantity; numbers and performance are equally important;
- if $s = 2$, then numbers don't count and only quality matters.[7]

Intermediate, noninteger values are "mixed" cases. The effects of numbers on combat effectiveness are shown in figure 7. If the parameter s is greater than one, then there are diminishing returns to numbers; if s is less than one, we observe increasing returns.[8]

We can now consider a question raised in chapter 3: What is the relative importance of performance versus quantity in combat effectiveness? Empirical studies using generalized Lanchester models (like system [4.5]) indicate a mixed case, somewhere between the linear and logarithmic cases. D. S. Hartley and K. L. Kruse

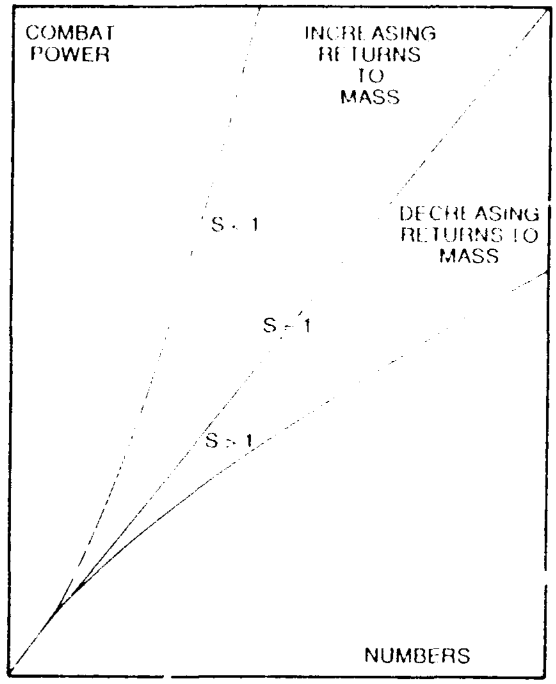

Figure 7

analyze the combat results using the Helmbold Ratio, which is defined as

$$H = (x_0^2 - x^2) / (y_0^2 - y^2), \qquad (4.7)$$

where x and y are forces remaining after the engagement.[9] Hartley and Kruse then proceed with an empirical model to explain combat results:

$$\ln(H) = v \ln(x_0/y_0) + w, \qquad (4.8)$$

where $\ln(H)$ is the natural logarithm of H, (x_0/y_0) is the starting force ratio, and v and w are parameters to be estimated.

Empirical results show the relative importance of performance and quantity in explaining combat results; that is, the value of v in model (4.8) corresponds to the value of s in system (4.5). In particular an estimated value of v greater than one supports the importance of numbers. Hartley and Kruse show that the estimated value of v corresponds to the value of a in equation (4.1) (or [2s] in equation (4.7)).[10] The results are shown in table 1.

Using model (4.8), Hartley estimated the value of v using air and land battle data.[11] The results presented in table 1 are easily interpreted. They are consistent with a mixed linear-logarithmic model of combat losses.[12] In terms of the effectiveness measure (4.1), that means quality is not everything, but it is more important than numbers.

One objection to this approach is that attrition is a simplistic measure of combat results. We reach the same basic conclusion with a more sophisticated assessment. The Quantified Judgment Model (QJM) uses a richer metric for land combat results, consisting of (1) mission accomplishment, (2) ability to hold ground, and (3) casualties incurred.[13]

Table 1

Hartley's Estimates of the Importance of Performance in Battle

Data Set	*Observations*	*v**	*Error*	R^2
Helmbold	92	1.23	0.12	.55
	81	1.49	0.12	65
Battle of Britain	17	1.54	0.28	.67
Civil War	19	1.60	0.27	.67
Inchon	19	1.37	1.38	.05
HERO	263	1.54	0.14	.32
	340	1.20	0.08	.38
	24	1.44	0.55	.23
Total	855	1.38	0.06	.41

Source: D. S. Hartley III, *Historical Validation of an Attrition Model* (Oak Ridge, Tenn.: Data Systems Engineering Organization, May 1990), 1–4.

* If $v>1$, then unit performance is estimated to be more important than numbers.

Using the QJM method of measuring combat results, T. N. Dupuy finds strong evidence of diminishing returns as more numbers are added to either side of an engagement:

> There is evidence from historical combat that, after a given ratio of combat power is reached, the addition of more forces provides less in terms of results than would otherwise be expected. . . . This is, of course, a statement of the familiar law of diminishing returns.[14]

Diminishing returns in combat are consistent with performance being more important than numbers, as illustrated in figure 7. Empirical studies support performance counting for more than quantity, and current emphasis on performance is consistent with that assessment of what counts in combat.

Weapons Design in a More Uncertain World

The post–cold war era has imposed major changes on US strategy, defense planning, as well as on the size and composition of forces. To a large extent, we have planned against a main enemy, the USSR, and a main contingency, a large Soviet invasion of NATO Europe via the Central Front.[15] There are two major developments in the planning environment.

1. The Soviet threat, at least as traditionally defined, has clearly diminished. However, major uncertainties remain regarding internal developments and the prospects for arms control agreements.

2. Various regional threats to national interests are more important, in absolute as well as relative terms.[16]

The most important implication for planners is greater uncertainty regarding actual military operations. Five years ago, for example, few observers would have rated an Iraqi seizure of Kuwait as the most likely contingency to require a military response. Consequently, the effectiveness of any military force is more uncertain as a variety of operational factors vary with contingency, including hostile forces, allied forces, basing access, weather conditions, and so forth. Without a compelling major scenario upon which to anchor planning, there is a greater need to reflect that uncertainty in planning and resource allocation decisions.[17]

Fortunately, an established body of knowledge, called portfolio theory, provides useful insights in planning for risky situations. In financial markets, investors may purchase a wide variety of assets, each having an expected return and a certain amount of risk attached. Portfolio theory deals with the selection of an optimal mix of assets (optimal "portfolio"). The theory also has some useful insights into cost-performance trade-offs in weapon system designs.[18]

A central assumption of the theory is that investors are risk averse, preferring less risky portfolios, other things being equal. Similarly, it is reasonable to suppose that defense planners are risk averse with respect to the capabilities of their forces in various combat situations.

Portfolio theory centers on utility maximization under conditions of uncertainty. Each asset has a return that depends upon general economic and specific market conditions. Employing probability distributions to estimate the likelihood of the various possible returns, the methodology computes both an expected value and a spread in returns, measured by variance or standard deviation in the return. Variability of return is the measure for risk.

If alternative portfolios are analyzed for risk (bad) and expected return (good), some candidate portfolios are eliminated and an efficient frontier emerges. (See curve AB in figure 8.) At any point on the frontier, one cannot find a portfolio with a higher rate of return without also increasing risk. The frontier slopes upward to the right, meaning that less risky assets have lower rates of return, and command a premium price in the market.[19]

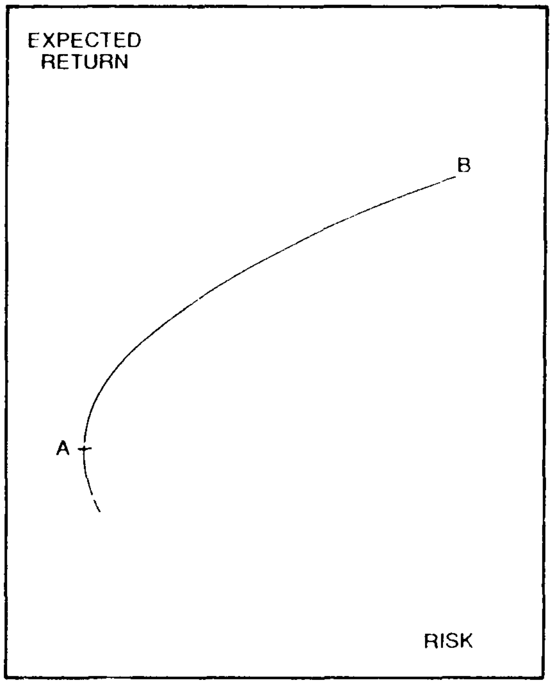

Figure 8

With the absence of a market and risk-free asset in weapons design, many of the results of portfolio theory do not apply directly to weapon design. However, the basic insights gleaned are very useful. We know that investors are willing to pay more for a less risky asset than a simple calculation of expected return implies.[20]

The optimum system design includes consideration of expected force effectiveness (good) and also variability in effectiveness (bad). To see the effects of risk aversion in design choices, we can revisit figure 6 and incorporate the effects of being risk averse by formulating an objective function to be maximized by design choice:

$$U = E(R) - A \text{ var}(R). \quad (4.9)$$

where U is the value of "utility" attached to a system design, $E(R)$ is expected effectiveness, var(R) is variability of effectiveness as employment conditions change, and A is a measure of risk aversion. If we don't care about risk, A is zero; increasing risk aversion is reflected in larger values of A.

Figure 9 shows the effects of risk aversion. If increased performance lessens risk, then the indifference curves rotate toward the vertical—as shown by MM' versus NN'. The result is that risk aversion increases system performance in the optimum design.

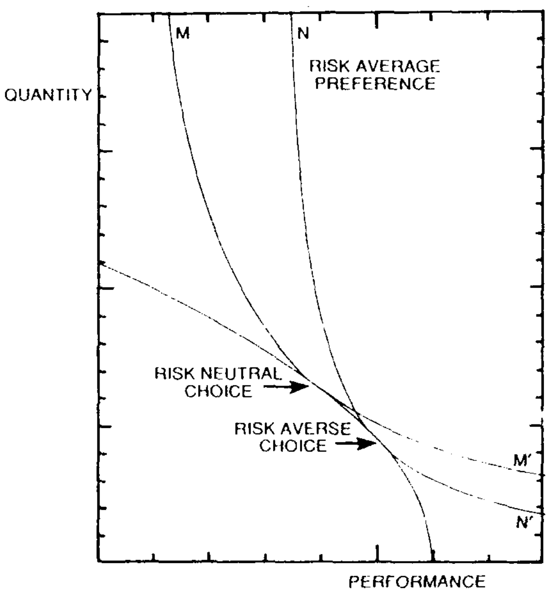

Figure 9

The implication is that if we lessen risk by increased performance, we should choose performance levels beyond that implied by expected value considerations. If increased performance increases risk, then the opposite conclusion applies.

There is no definite answer to the question of whether performance reduces risk, but some results using the TAC Warrior model of air combat in Europe are interesting and suggestive. A major simulation study, documented by Frederick L. Frostic, explicitly considers quantity-performance issues in tactical air forces—through analysis of equal-cost combinations of high-performance F-15s versus cheaper, "austere" fighters.[21]

The base case for the simulation included clear air mass conditions. One excursion considered degraded weather. Results showed that as weather conditions deteriorated, the effectiveness of the lower-performance option was lessened *much more*: "The austere day fighter (effectiveness) . . . is significantly degraded," while the F-15 option improves slightly.[22] In terms of portfolio theory, Frostic's results indicate higher system performance means less variability in combat performance.

Frostic's conclusions are only suggestive. Franklin C. Spinney, for example, has argued that the maintainability of the more complex F-15 in combat is also a source of risk.[23] We need more study of such risks before reaching any definite conclusions. Some evidence shows that higher-performance designs lessen risk, and that rational designers should therefore show a special willingness to pay for more quality in system designs.

Implications for Planning

This chapter has considered some factors pertaining to design practices in the post–cold war era. There are two major considerations. First, past emphasis on performance seems consistent with historical evidence. Second, more uncertainty in force planning may favor continued emphasis on system performance as a means of reducing risk. Though it is worthwhile to rethink how we design weapon systems, there is some good evidence that no radical changes are necessary.

Notes

1. Frederick William Lanchester, "Mathematics in Warfare," report in *The World of Mathematics*, ed. James R. Newman (1916; New York: Simon and Schuster, 1956), 2138–57.

2. Dick Cheney, *Report of the Secretary of Defense to the President and the Congress* (Washington, D.C.: Government Printing Office, January 1991), 1–7.

3. Lanchester, 2145.

4. The right-hand side of equation (4.4) is a monotonic transformation of $q_x x^2$. Both functions lead to the same optimal system design. William J. Baumol, *Economic Theory and Operations Analysis*, 4th ed. (Englewood Cliffs, N.J.: Prentice-Hall, 1977), 214–16.

5. D. S. Hartley III, *Historical Validation of an Attrition Model* (Oak Ridge, Tenn.: Data Systems Engineering Organization, May 1990), 1–4; James G. Taylor, *Force-on-Force Attrition Modeling* (Monterey, Calif.: Naval Postgraduate School, 1980), 37–39.

6. In terms of equation (4.1), $a = 1/(2-s)$.

7. For $s = 0$, $a = .5$ in equation (4.1); for $s = 1$, $a = 1$, with quality and quantity being equally important; for $s = 2$, a is infinite.

8. Dupuy diminishing returns indicate the importance of "economy of force." T. N. Dupuy, *Understanding War: History and Theory of Combat* (New York: Paragon House, 1987), 125–48. Lanchester in discussing the case $s = 0$ emphasizes the importance of "mass" and concentration. Lanchester 2138, 2142–44, 2148–57.

9. Hartley, *Historical Validation*, 3.

10. D. S. Hartley III and K. L. Kruse, *Historical Support for a Mixed Law Lanchestrian Attrition Model* (Oak Ridge, Tenn.: Data System Engineering Organization, 1989), 9–11.

11. Seven sets of land warfare data: four from Helmbold over extended periods, the US Civil War, plus daily observations from the Inchon campaign; three sets from the HERO Land Warfare Database. Also 18 engagements from the Battle of Britain. Hartley, *Historical Validation*, 5. D. S. Hartley III, *Confirming the Lanchestrian Linear-Logarithmic Model of Attrition* (Oak Ridge, Tenn.: Data Systems Research and Development Program, 1990), 5–6.

12. Hartley, *Historical Validation*, 49; Hartley, *Confirming the Lanchestrian Linear-Logarithmic Model*, xi, 1–5, 75–76.

13. Dupuy, 280–81.

14. Ibid., 125–26.

15. Cheney, v.

16. Ibid., v, ix.

17. With a main scenario, such as the Central Front, one could size forces against the contingency and feel reasonably confident that the forces thus provided would be more than adequate to handle lesser contingencies.

18. Fabian and Franck discuss applications of portfolio theory to acquisition planning in a somewhat different context. Felix M. Fabian, Jr., and Raymond E. Franck, Jr., "A Portfolio Approach to Systems Acquisition," *NMCA Journal*, Summer 1977.

19. If the efficient frontier were to slope the other way (downward to the right), then points on the left edge of the frontier would dominate those to the right—having higher expected returns and lower risks. Price and return are inversely related. At a return of 8 percent, the cost of a bond that pays $100 five years from now is $68.06; at 12 percent, price falls to $56.74.

20. This is part of the Capital Asset Pricing Model. Harold Bierman, Jr., and Seymour Smidt, *The Capital Budgeting Decision*, 6th ed. (New York: Macmillan, 1984), 427–39. More formally, an asset included in the optimal portfolio must satisfy the following condition:

$E(R_i) = V + 2\,A\,w_i\,\mathrm{var}(R_i) + 2\,A\,w_i\,\mathrm{cov}\,(R_i, R_{-i})$,

where (R_i) is the ith asset's return, $E(R_i)$ is expected return, var (R_i) is variance of return, w_i is the ith asset's fraction of total portfolio value, $\mathrm{cov}(R_i, R_{-i})$ is the covariance of the ith asset's return with the return from the rest of the portfolio, and V is the marginal value of funds to invest. $E(R_i)$ is the required rate of return for the ith asset to attract investors. Everything else constant, as var (R_i) decreases, required rate of return decreases. That means rational investors pay a premium price for less risky assets. More often, one hears of sellers of more risky assets paying a "risk premium" in terms of rate of return.

21. Frederick L. Frostic, "Quality Versus Quantity in Tactical Fighter Forces," *Journal of Defense Research* 13 (1981): Declassified 1987, 297.

22. Ibid., 301.

23. Franklin C. Spinney, *Defense Facts of Life: The Plans/Reality Mismatch* (Boulder, Colo.: Westview Press, 1985), 32–37.